Experimentally determining cold nuclear matter effects on the J/ψ at RHIC

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Acknowledgements

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* The heavy lifter!

The goal

Isolate those effects on J/ψ production in Au+Au collisions that are due to hot nuclear matter effects in the final state.

Do this by analyzing p+Au (or d+Au) data to understand how J/ψ production is modified when it occurs in a nuclear target.

Any such attempt implies that the effects of production in a nuclear target and the effects of the hot final state can be factorized.

A note on time scales in nuclear collisions (RHIC)

At 100 GeV/nucleon (200 GeV/nucleon center of mass) the colliding nuclei have **γ = 100**. Time scales are roughly:

Nuclear crossing time ~ 0.1 fm/c. ← **CNM effects**
J/ψ meson formation time ~ 0.3 fm/c
QGP thermalization time ~ 0.3 to 0.6 fm/c
QGP lifetime ~ 5-7 fm/c
J/ψ lifetime (free space) ~ 2000 fm/c

The creation of the charm pair that evolves into the J/ψ and its modification in the **hot** medium occur on different time scales. They are often taken as being factorizable.

If so, we can study the cold nuclear matter (CNM) effects using p+A.

Cold Nuclear Matter effects

Consider two effects that modify the production of the initial J/ψ precursor poulation in a nuclear target:

• **Shadowing:** Modification of the effective parton densities at low x in nuclei.

• **Breakup:** of the bound precursor state due to collisions with nucleons that pass through the production point after the hard process.

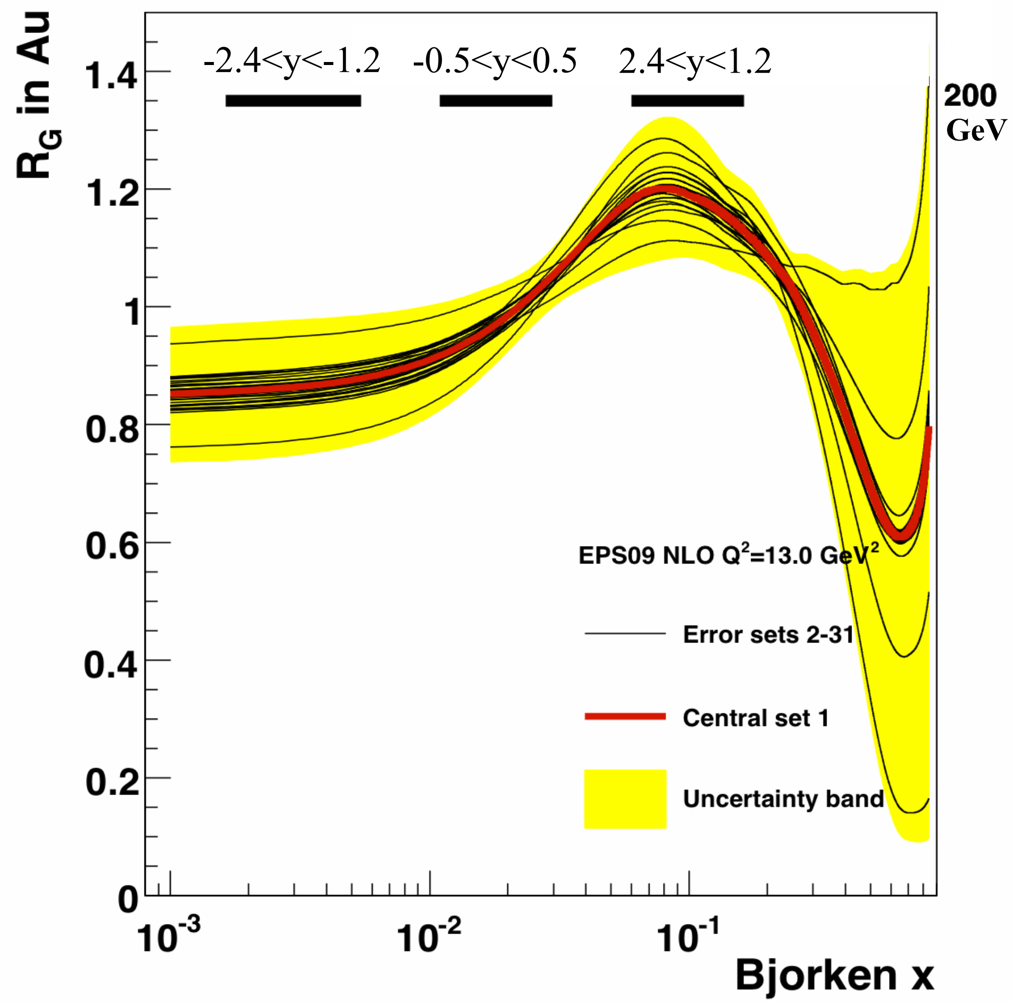
We do not, for now, consider other possible cold nuclear matter effects, such as **initial state energy loss.**

Shadowing: R_G for J/ψ production at RHIC

EPS09 **gluon** modification vs x at $Q^2 = 13\ (M^2 + \langle p_T \rangle^2$ for the J/ψ).

It will be important later to know that the input DIS and p+A data have no impact parameter information - **the modification is averaged over the nucleus**.

The approximate **x ranges** sampled by PHENIX at 200 GeV are shown.

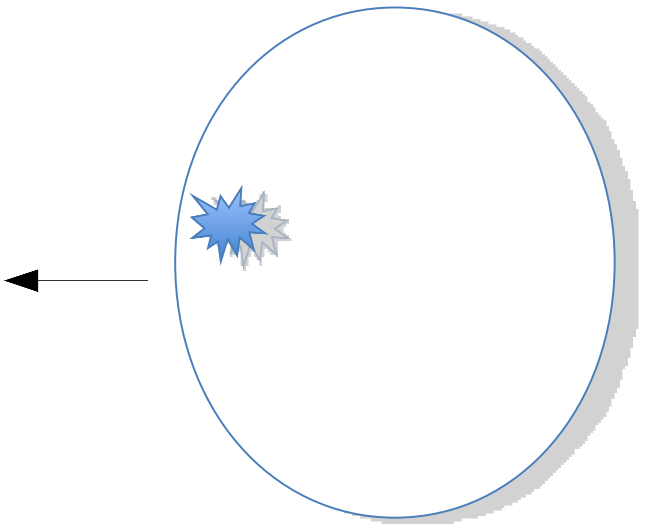


Breakup

After a bound charm pair is produced in the Au nucleus, it can be broken up by a collision with a nucleon that passes through the production point later.

Account for this loss using a cross section, σ_{br}. In general, depends on $\sqrt{s_{NN}}$ and rapidity – not much theoretical guidance!

It also depends on **which state** (J/ψ, ψ', χ_c), so when we use one value of σ_{br} we are mocking up the breakup of all states that result in a J/ψ.

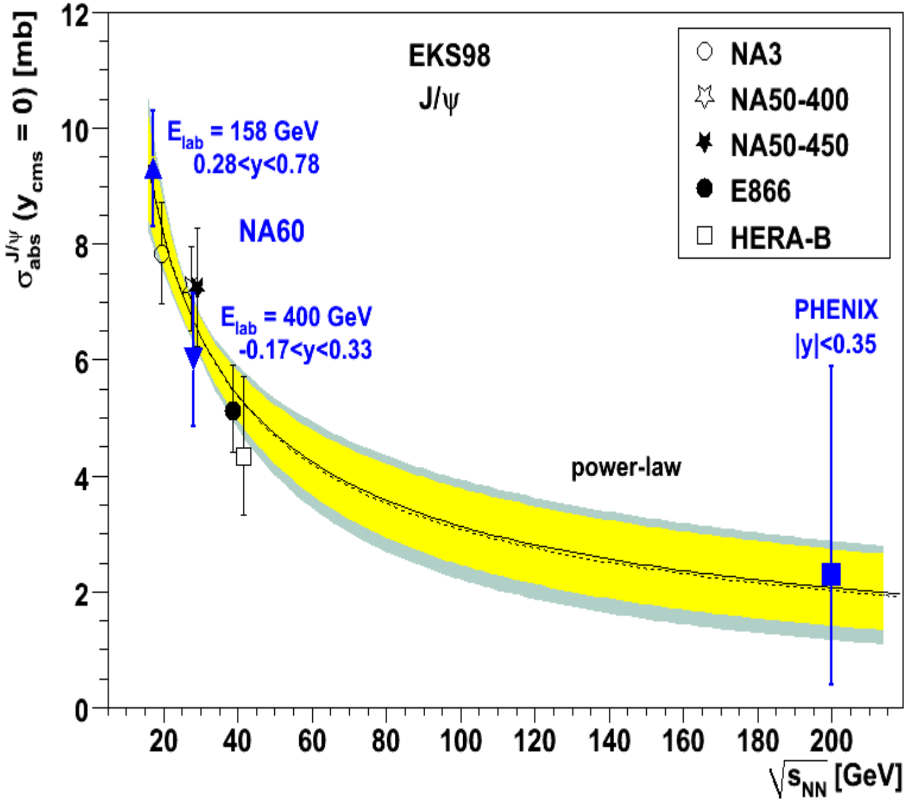


Shadowing plus J/ψ breakup cross section

Lourenco, Woehri and Vogt made a systematic analysis at y~0 using EKS98 + σ_{br} and saw a clear **collision energy dependence** of σ_{br}.

The PHENIX data point shown here is from the 2003 d+Au run.

JHEP 0902:014 (2009)



σ_{br} may depend on rapidity also.

Shadowing plus J/ψ breakup cross section

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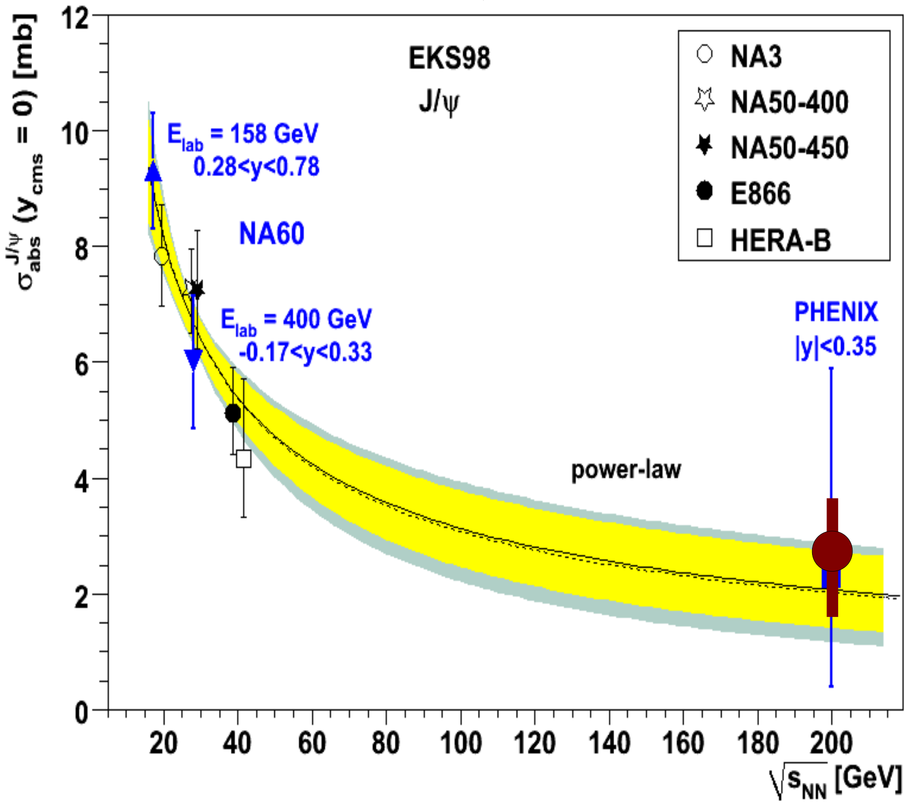
The PHENIX data point shown here is from the 2003 d+Au run.

Add a PHENIX point from the 2008 run (2.7 +1.1 -1.2 mb)

σ_{br} may depend on rapidity also.

JHEP 0902:014 (2009)



Methodology for parameterizing CNM effects

- Use a Glauber model for d+Au collisions (includes trigger effects)
- Sort d+Au collisions into **experimental centrality bins**
- Reduce each d+Au collision to two p+Au collisions
- For each NN collision
  - Calculate loss due to σ_{br}
  - For each experimental rapidity and p_T bin
    - Estimate Bjorken x_2, and Q^2
    - Calculate nPDF modification
- Average $R_{dAu} = (\sigma_{br}$ loss) x (nPDF mod.) over all NN collisions

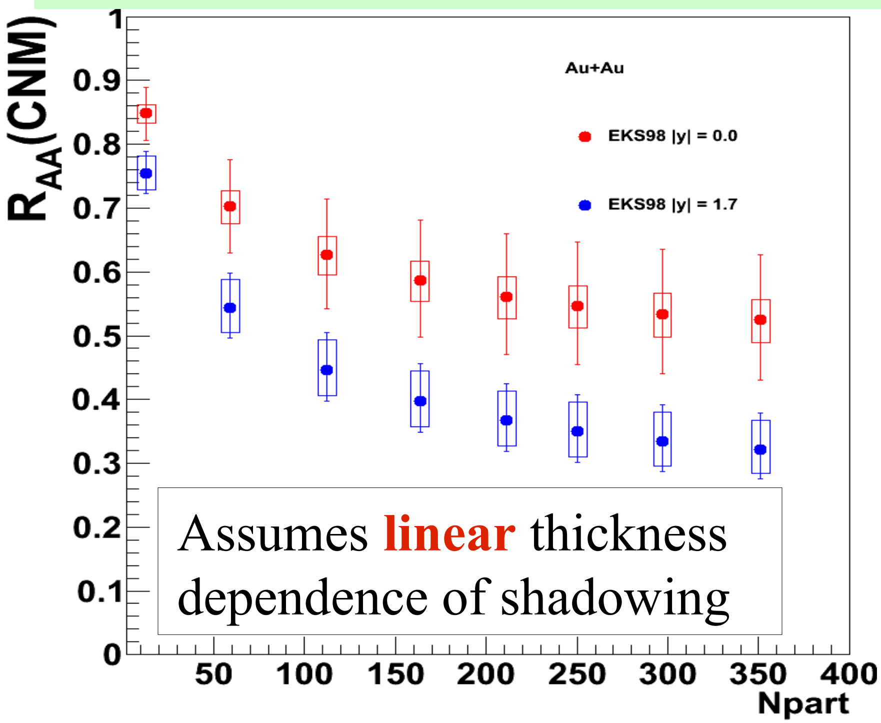
One can then vary σ_{br} to fit the data.

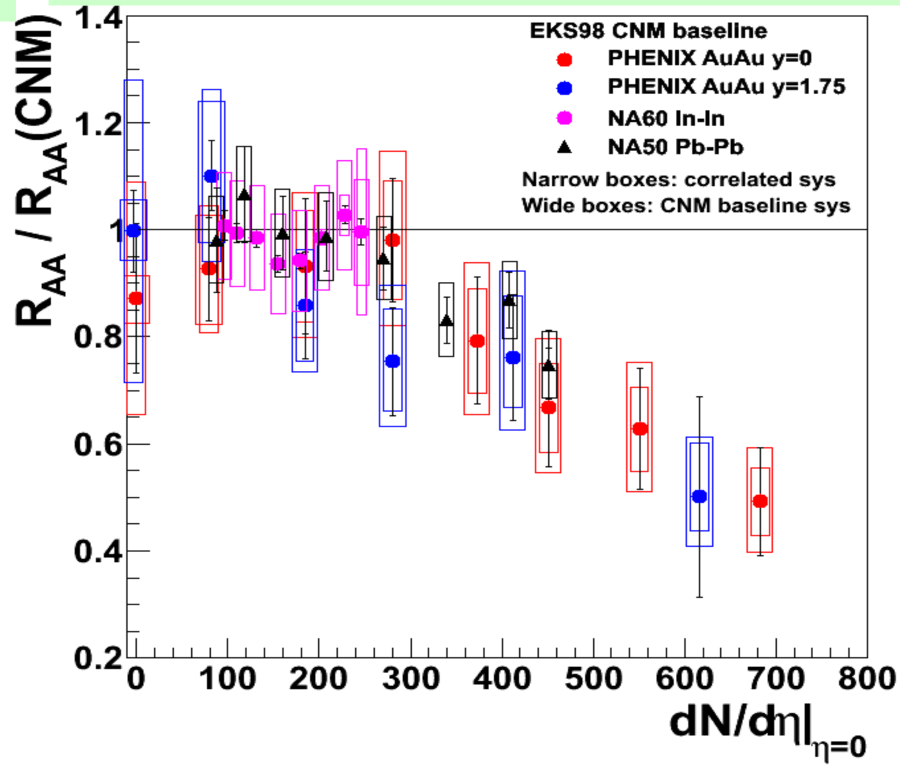
History: Cold nuclear matter R_{AA} – first attempts

Both PHENIX d+Au and NA60 p+A data at 158 GeV have been used to estimate cold nuclear matter contributions to R_{AA}.

Predicted Au+Au CNM R_{AA} from Glauber model, R. Vogt EKS98 calculation + $\sigma_{breakup}$ fitted to preliminary PHENIX d+Au R_{CP} (Frawley, INT 2009)

Comparison of PHENIX Au+Au R_{AA}/R_{AA}(CNM) with similar data from NA60 for In-In and Pb-Pb (NA60, arXiv:0907.5004) plotted vs multiplicity.





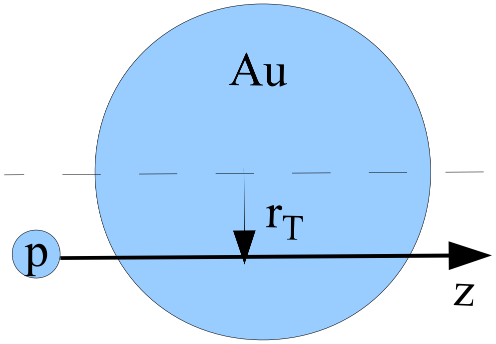
Back to now: Final PHENIX results

The final PHENIX results, now including $\mathbf{R_{dAu}}$, were released last year (**arXiv:1010:1246**).

To discuss them, I need the longitudinal density integrated nuclear thickness in Au at impact parameter r_T. It has units fm^{-2}:

$$\Lambda(r_T) = \int dz\, \rho(z, r_T)$$

Where z is the longitudinal distance in the projectile direction and $\rho(z,r_T)$ is the nuclear density at z and r_T, obtained from a Woods Saxon distribution.



To calculate the effect of σ_{br}, **start the integral** at z_1, the production point for the J/ψ precursor.

Final PHENIX d+Au J/ψ results - surprise!

- Plot MB R_{dAu} on X axis
  - (**overall** modification)
- Plot R_{CP} on Y axis
  - (**ratio** central/peripheral)
- Add data at 12 rapidities

In a d+Au Glauber model, try the **purely mathematical** dependencies:

$$M(r_T) = e^{-a\Lambda(r_T)}$$

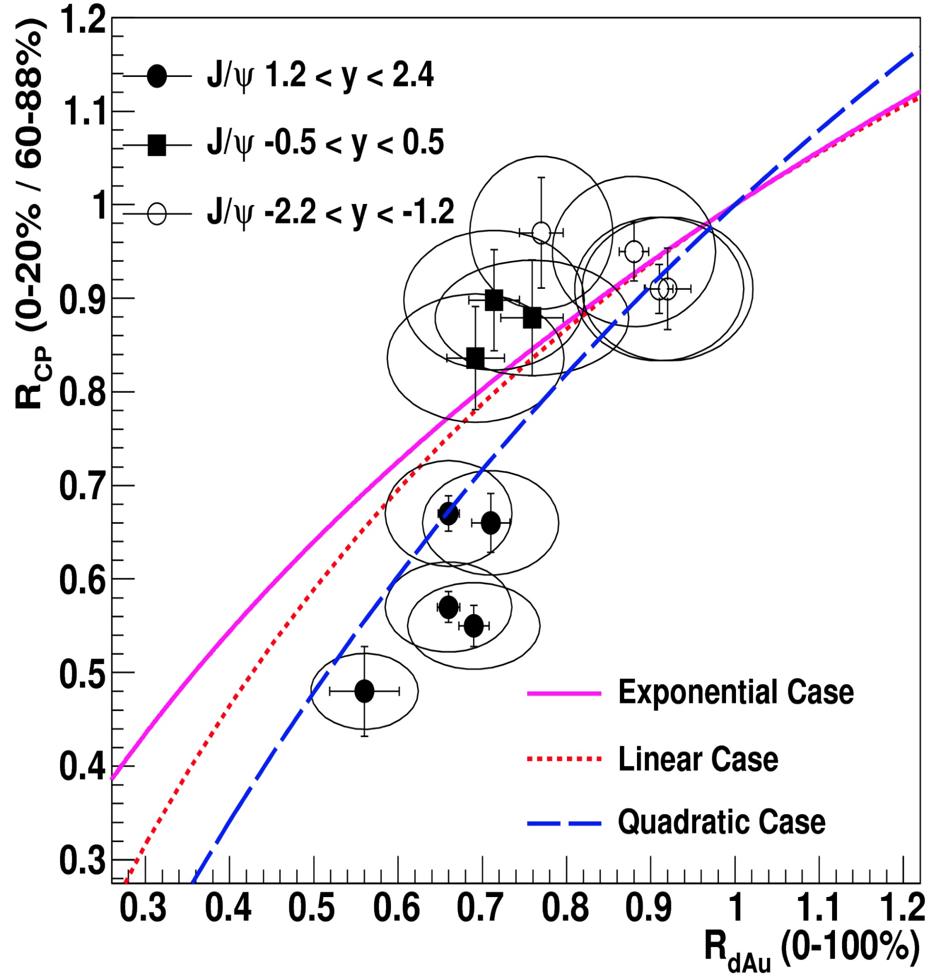
$$M(r_T) = 1 - a\Lambda(r_T)$$

$$M(r_T) = 1 - a\Lambda(r_T)^2$$

Vary the strength a, we see a **locus** for each dependence.

$y > 1.2$ data **not** consistent with linear thickness dependence

PHENIX: arXiv:1010.1246



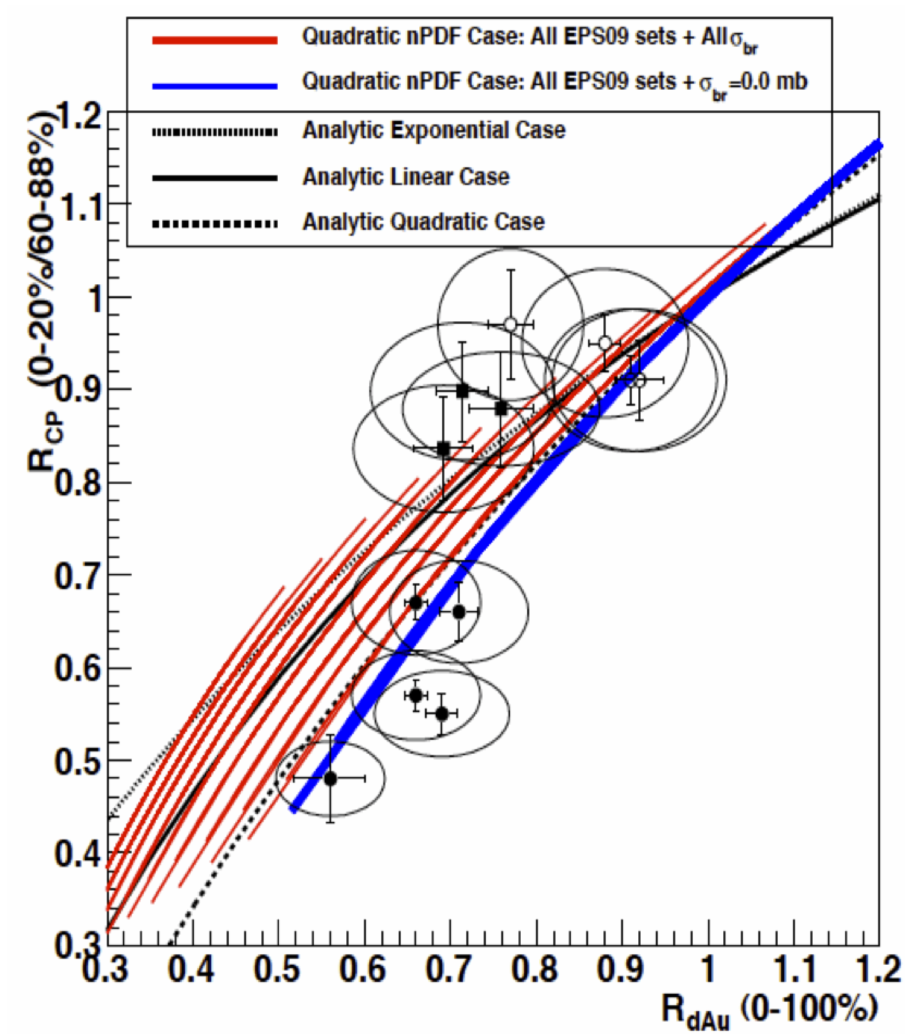
Adding more realism does not help

More realistically, the modification will combine a breakup cross section (exponential) with shadowing.

This shows a Glauber calculation using a combination of EPS09 with **quadratic** $\Lambda(r_T)$ dependence, and a range of breakup cross sections.

A significant breakup cross section worsens agreement with the data at $y > 1.2$.

Nagle et al., arXiv:1011.4534



How to proceed?

Explore what the data want by fitting the centrality dependence **independently** at all 12 rapidities.

At each rapidity, try a shadowing power of **1-20**, and optimize σ_{br} for each power.

Choose the power and σ_{br} to minimize χ^2.

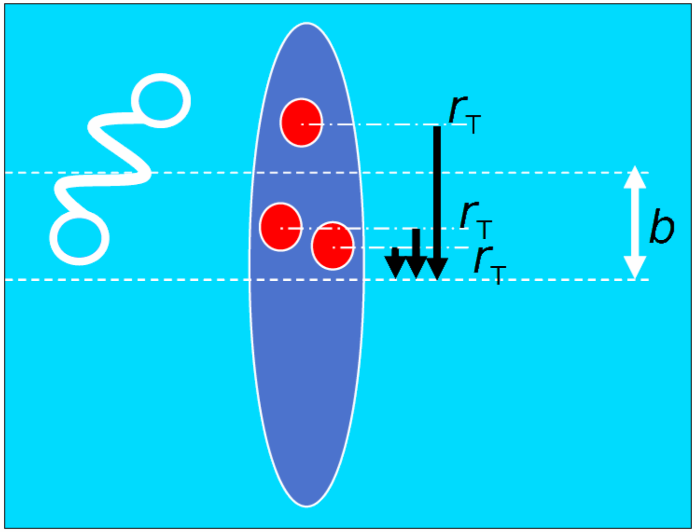
Assign an **uncertainty** corresponding to where χ^2 increases by 1.

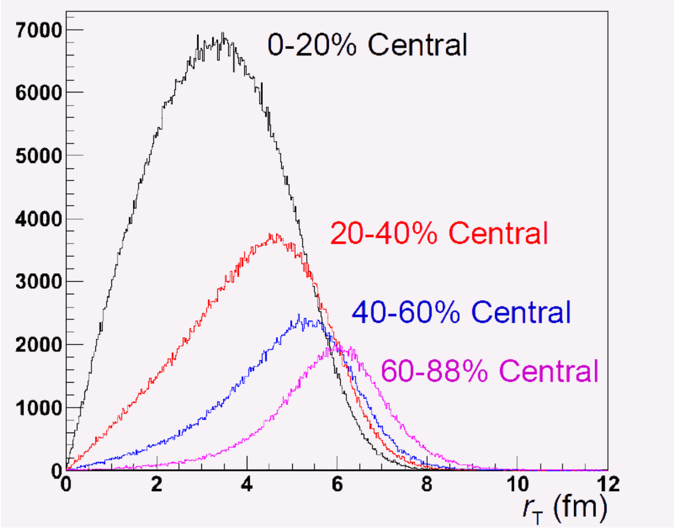
Fit the d+Au data using a Glauber model

Implement **shadowing** + $\boldsymbol{\sigma_{br}}$ nuclear modification in a Glauber model of the d+Au collision:

- Throw a d+Au collision
- Assign it to a **centrality** bin
- For each NN collision:
  - Use $\mathbf{r_T}$ to calculate the "thickness" Λ
  - Calculate x_2 and Q^2 for each rap. y
  - Use Λ to get shadowing
  - Use $\Lambda(z_1)$ to calculate breakup
- Calculate the average R_{dAu} at each y

Can then vary σ_{br} to **optimize** $\boldsymbol{\chi^2}$.





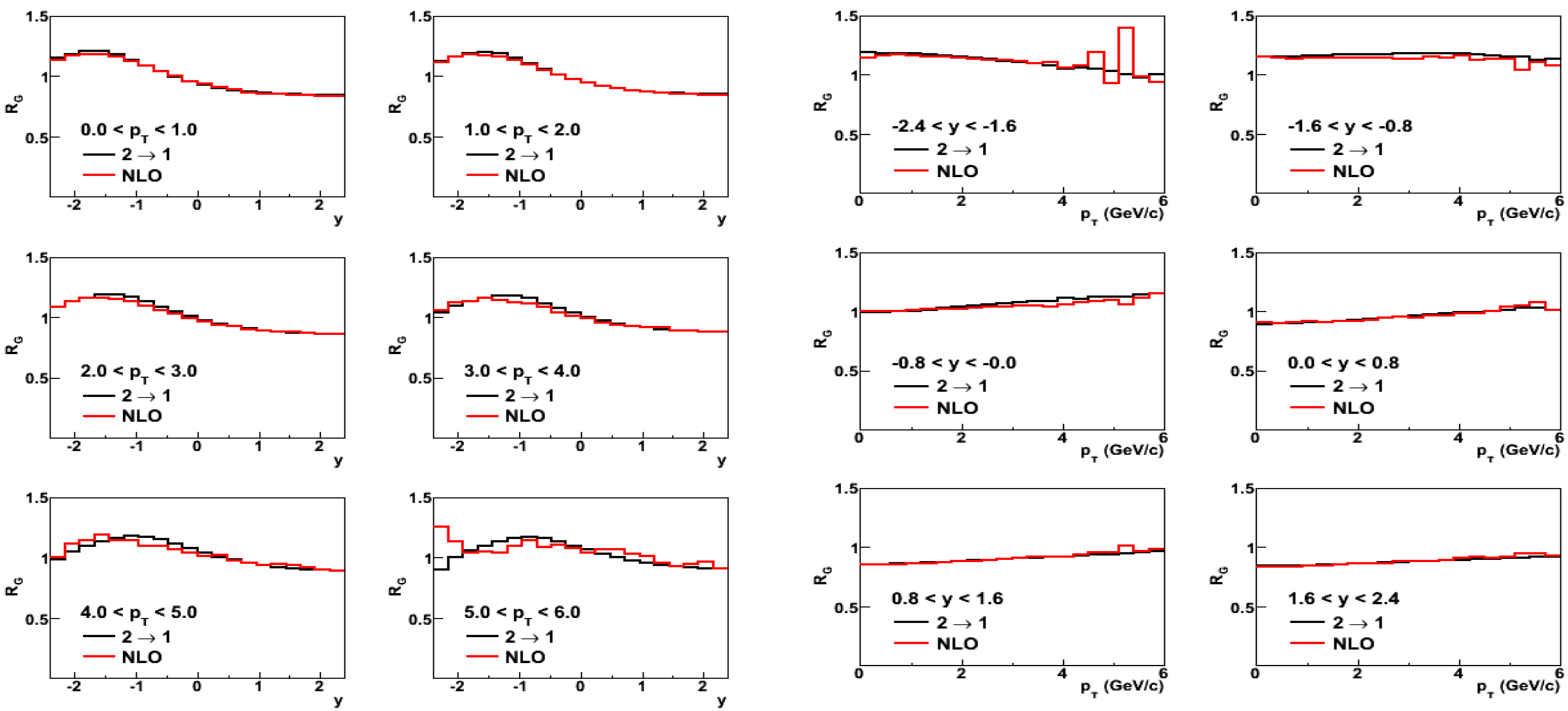
How to get x_2 and Q^2?

We assume **2→1 kinematics**.

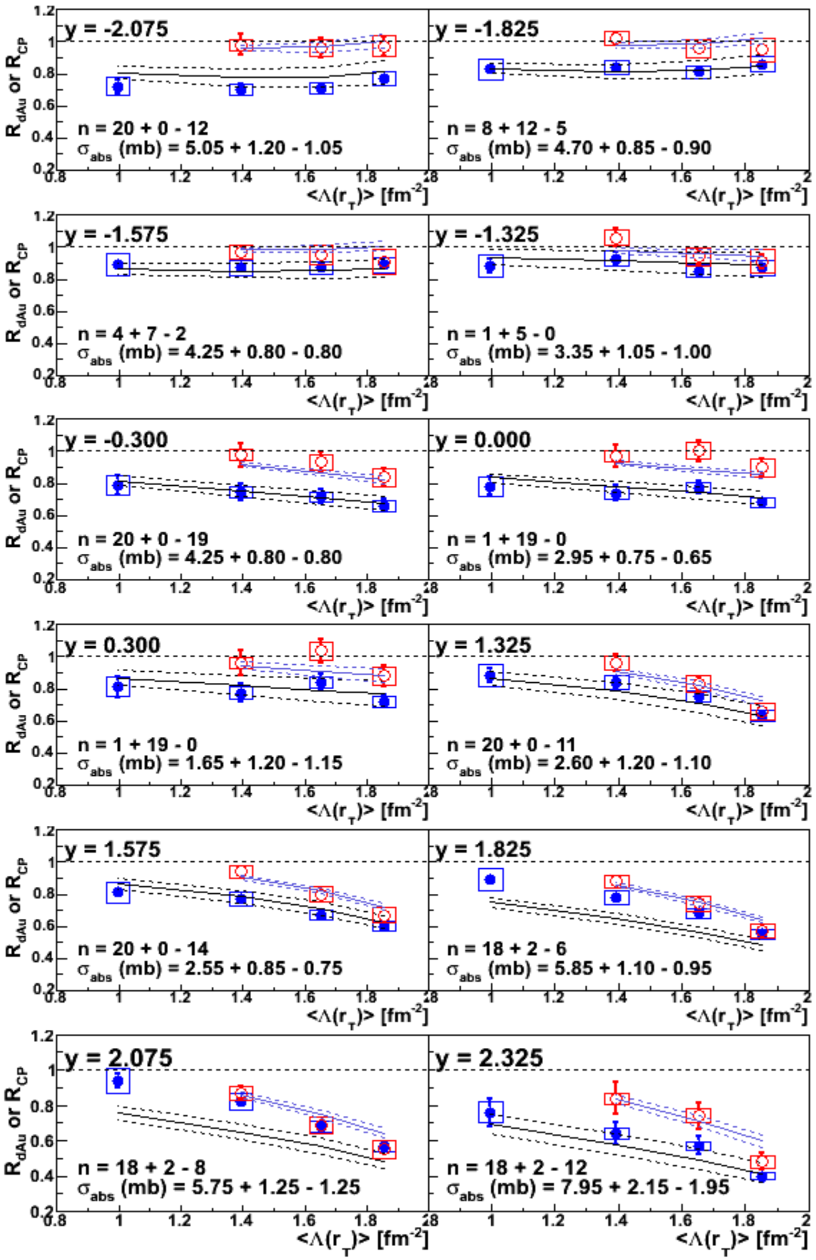
Not quite correct - but R_G obtained with x_2 and Q^2 from an NLO calculation by Ramona is very similar.

$$x_2 = \frac{\sqrt{M_J^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y}$$

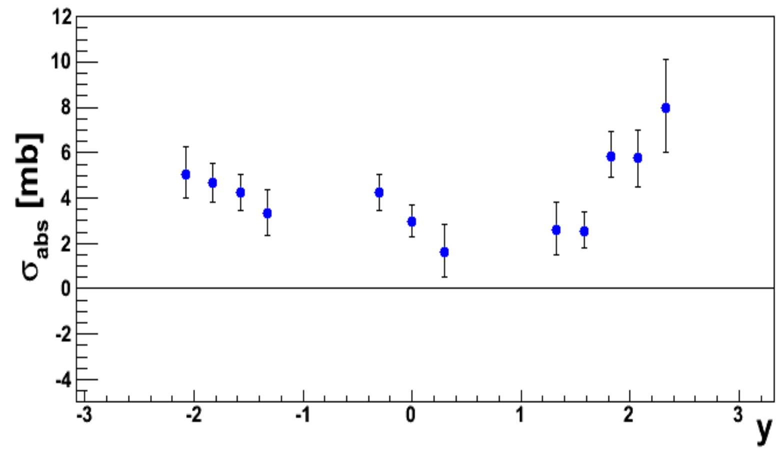
$$Q^2 = M_{J/\psi}^2 + p_T^2$$

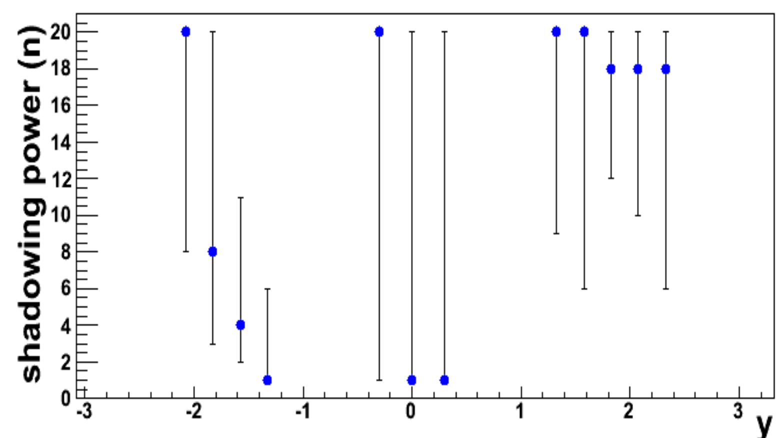


Fits for 12 rapidities



Determine shadowing power and σ_{br} independently at 12 rapidities. Vertical bars are 1σ (stat + sys).





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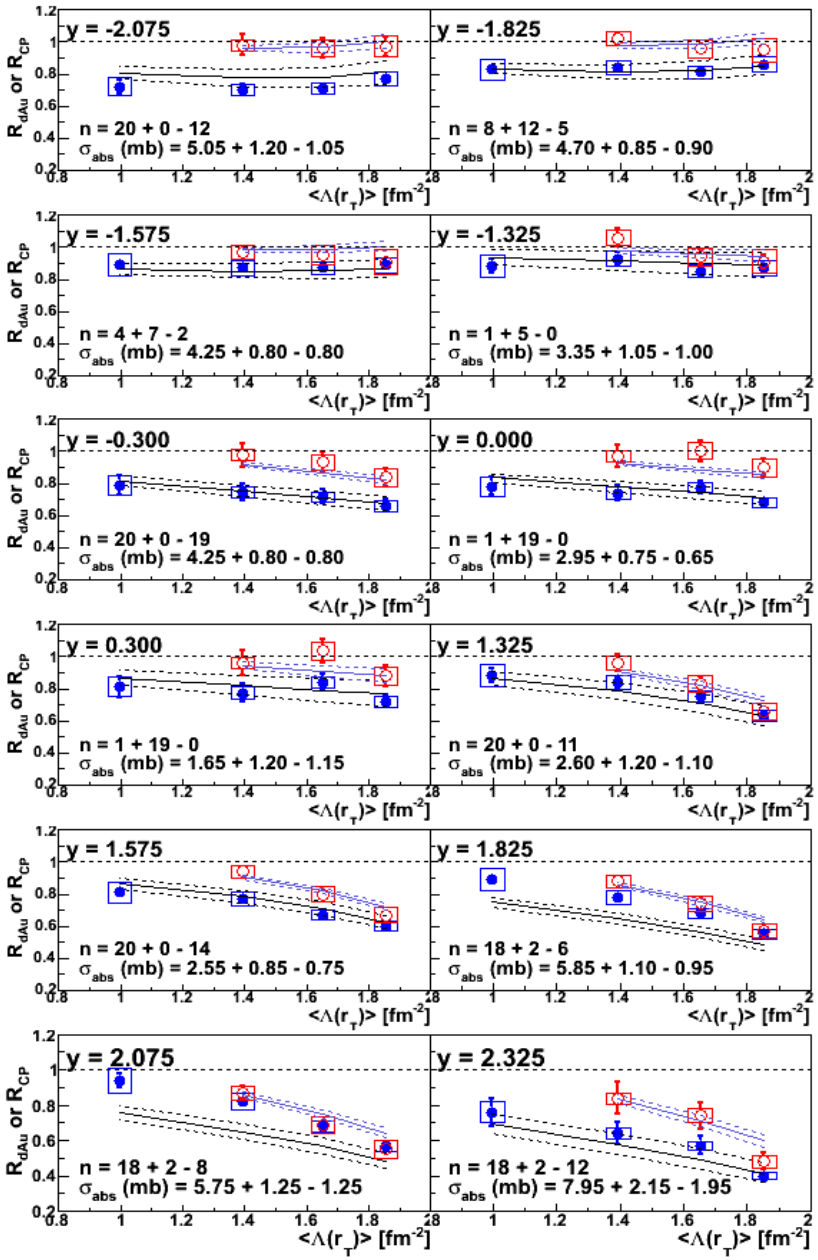

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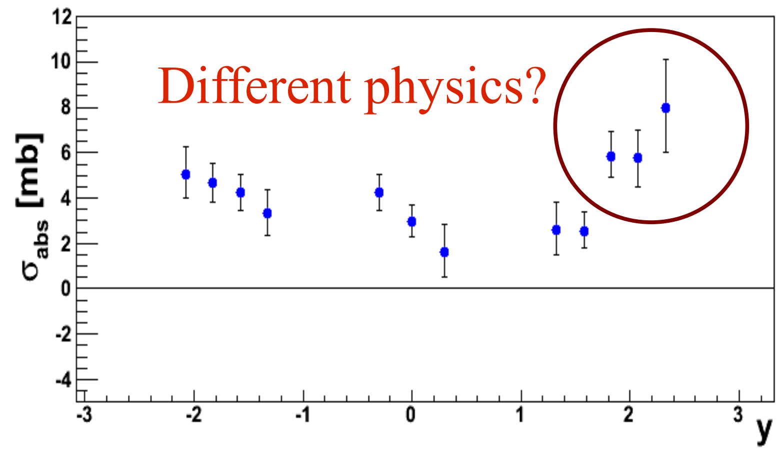
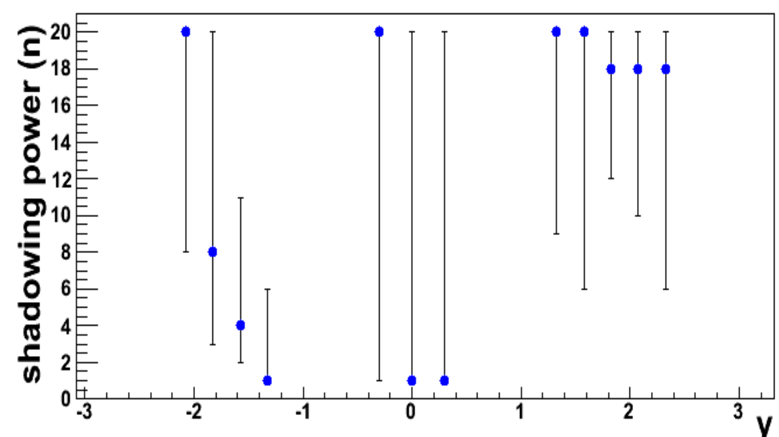




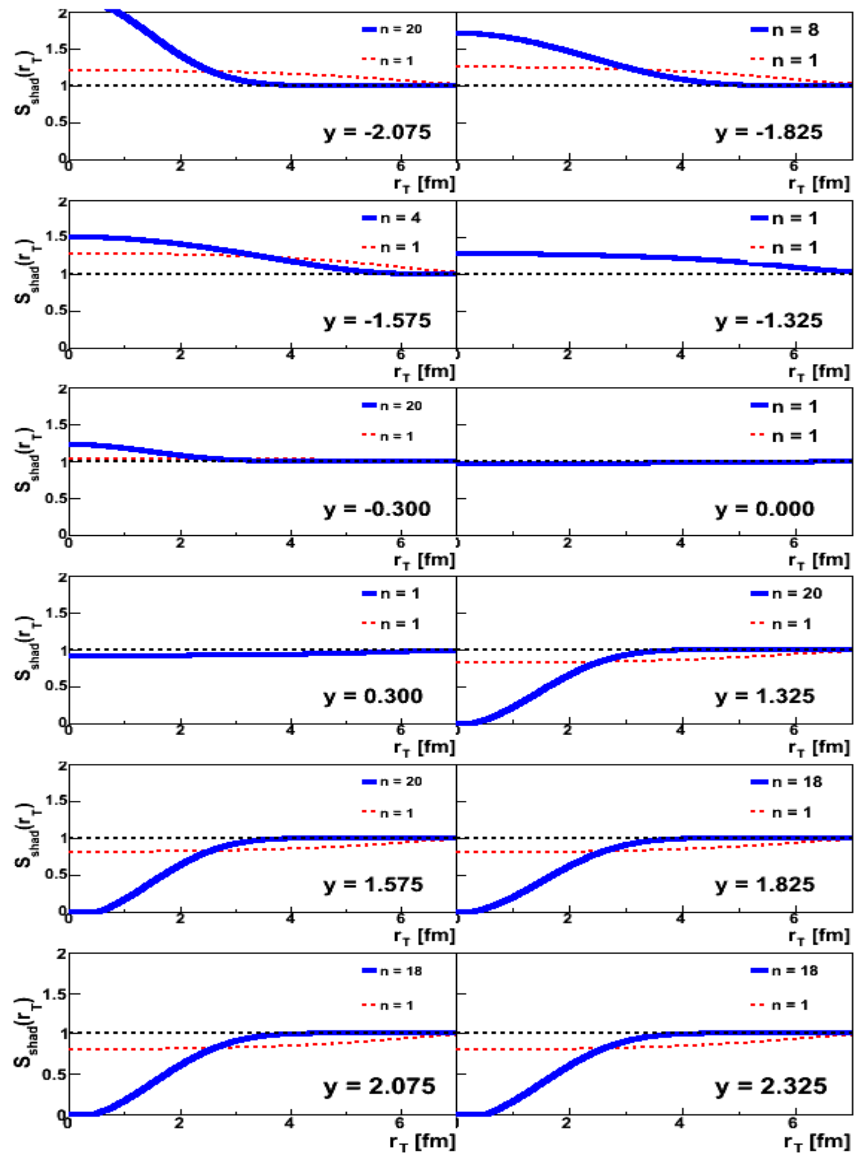
Shadowing modification vs r_T from the fit results

The shadowing modifications calculated with the best fit results are in **blue**.

The **red** curve shows linear thickness dependence of shadowing (for reference).

Where shadowing is strong, the modification turns on suddenly at $r_T \sim$ 3-4 fm.

It should be noted that this is the behavior **predicted for CGC** at large y. For anti-shadowing too?



Finally, Let's try to get R_{AA}(CNM)!

Fit the d+Au data in three rapidity bins:

$-2.4 < y < -1.2$

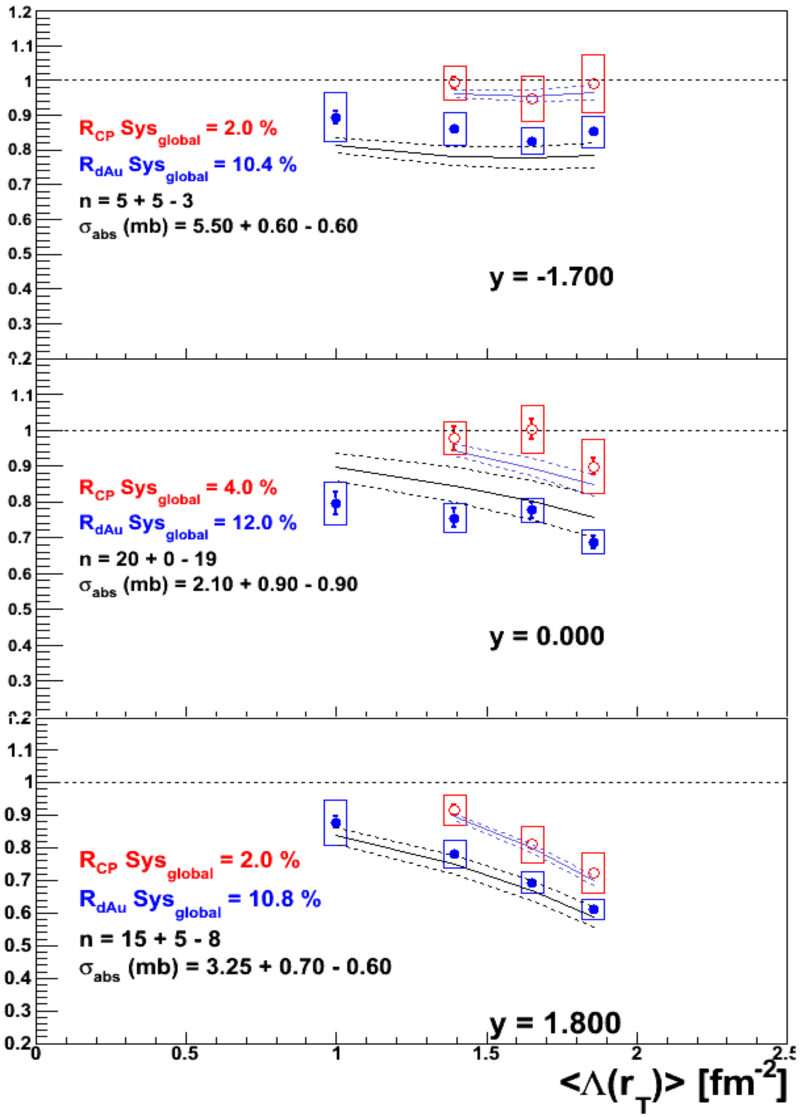
$-0.5 < y < 0.5$

$1.2 < y < 2.4$

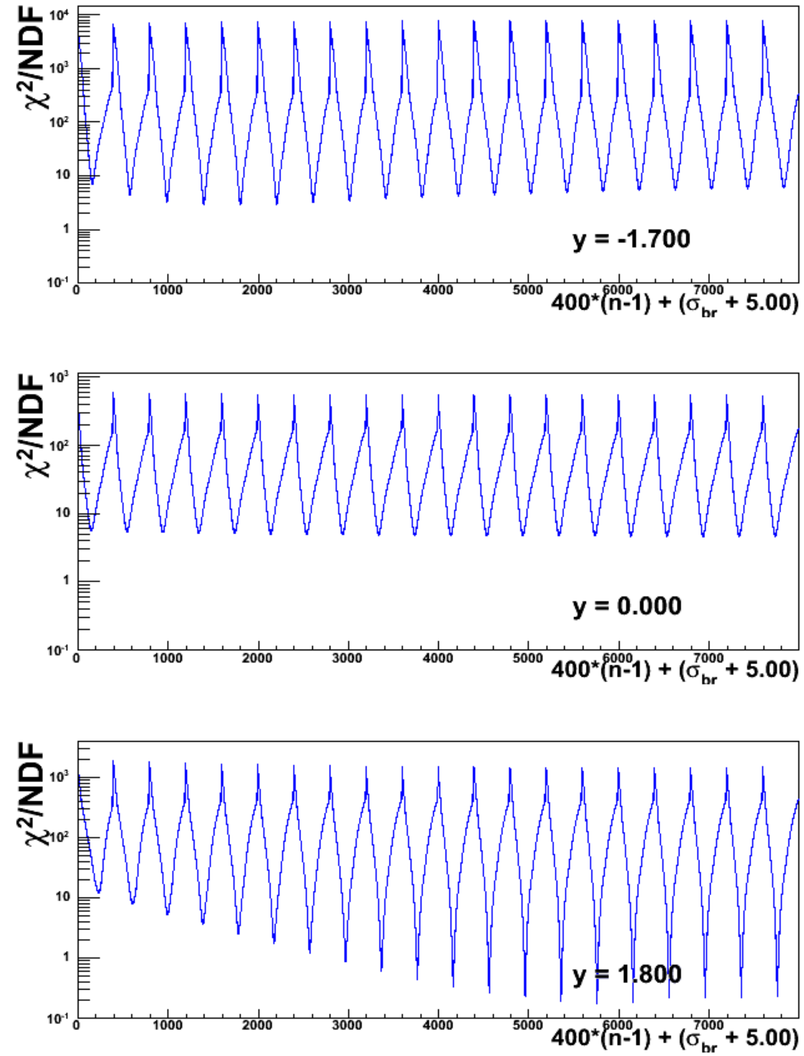
Sample the measured distributions of y and p_T from p+p data for each rapidity bin to estimate x_2 and Q^2 values.

Fits for three rapidities

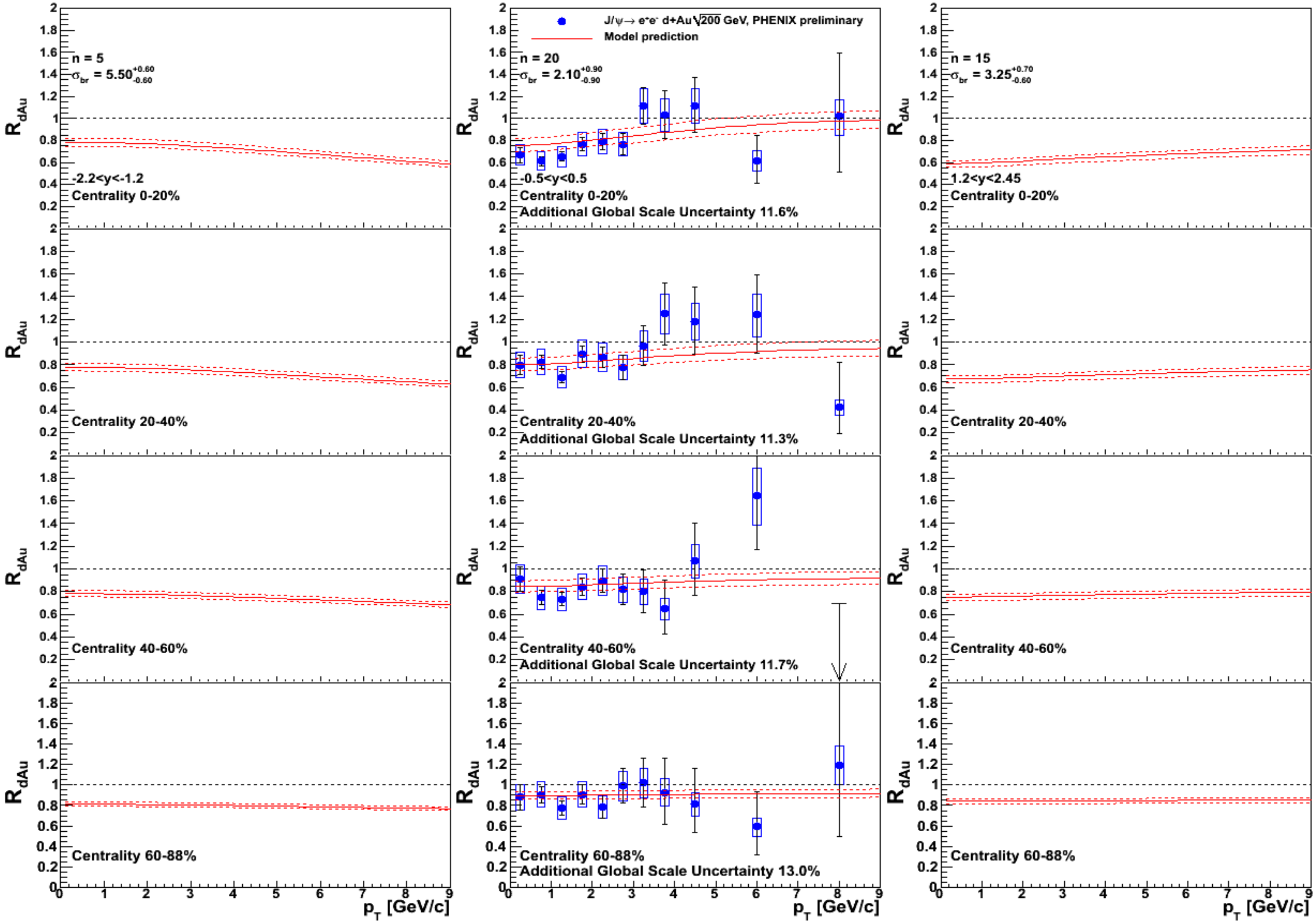
R_{dAu} or R_{CP} vs $\langle \Lambda(r_T) \rangle$



Map of χ^2/NDF vs σ_{br} for n=1-20



Sanity check: predict dAu p_T dependence from fits



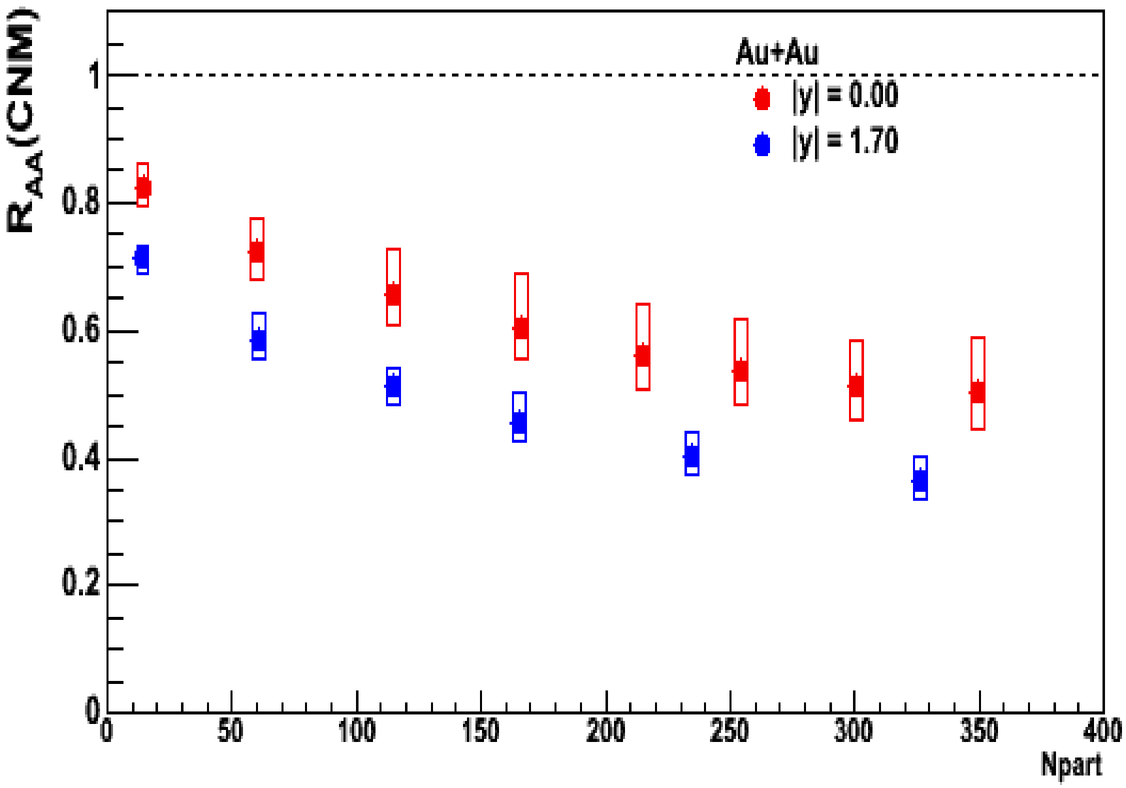
Calculating R_{AA}(CNM)

Now we can take the fit results and put them into a Au+Au Glauber model, to get the CNM contributions to the R_{AA}.

The fit uncertainties in σ_{br} are propagated to the result as a systematic uncertainty.

Calculated R_{AA}(CNM) – centrality dependence

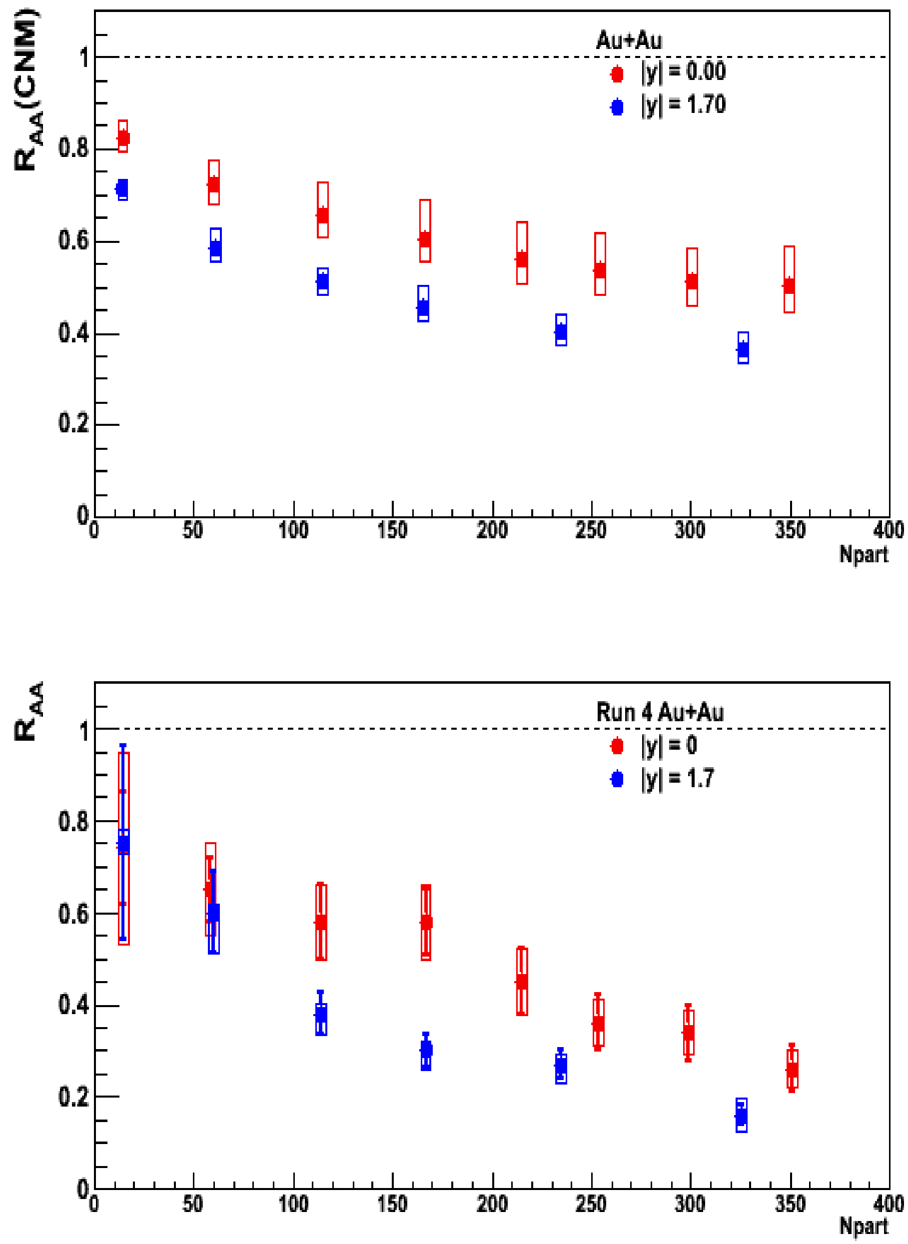
The parameterization of the d+Au data predicts significantly stronger CNM suppression in Au+Au at forward rapidity.



Compare R_{AA}(CNM) with R_{AA}

Now we can "correct" the measured R_{AA} for CNM effects by dividing it by R_{AA}(CNM).

The uncertainties from both numerator and denominator have to be combined.

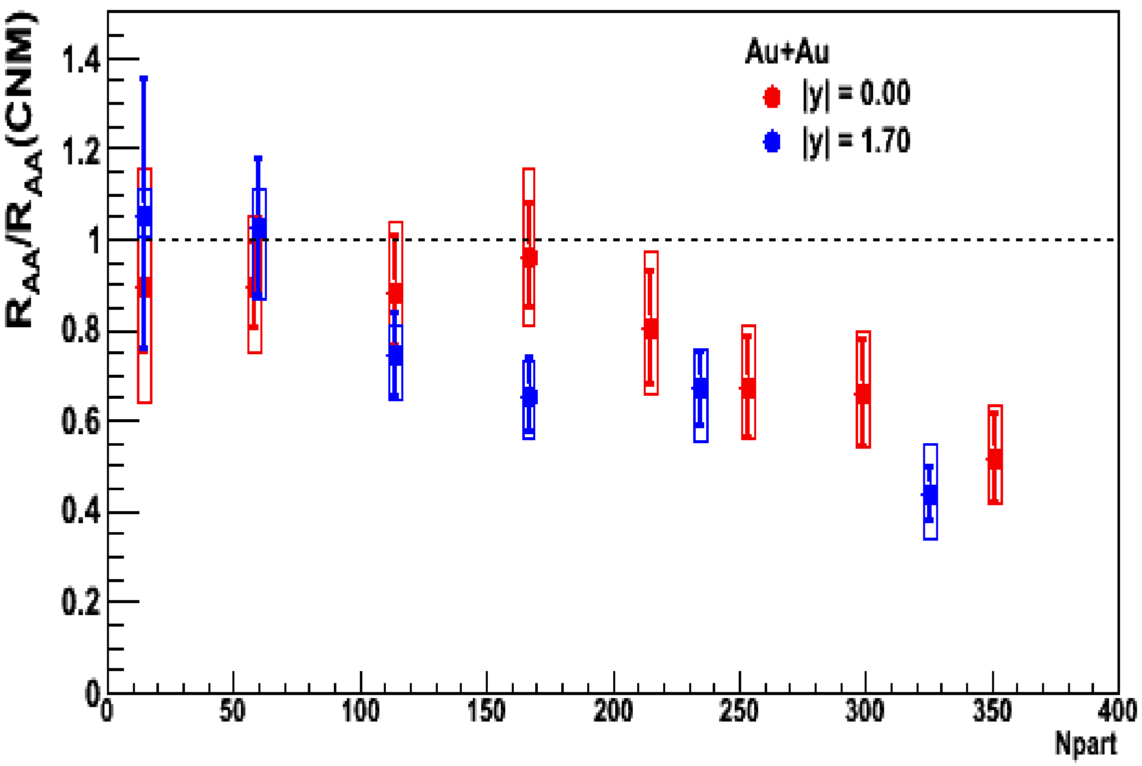


$R_{AA}/R_{AA}(CNM)$ – centrality dependence

Consistent with no suppression (beyond CNM) for Npart < 100

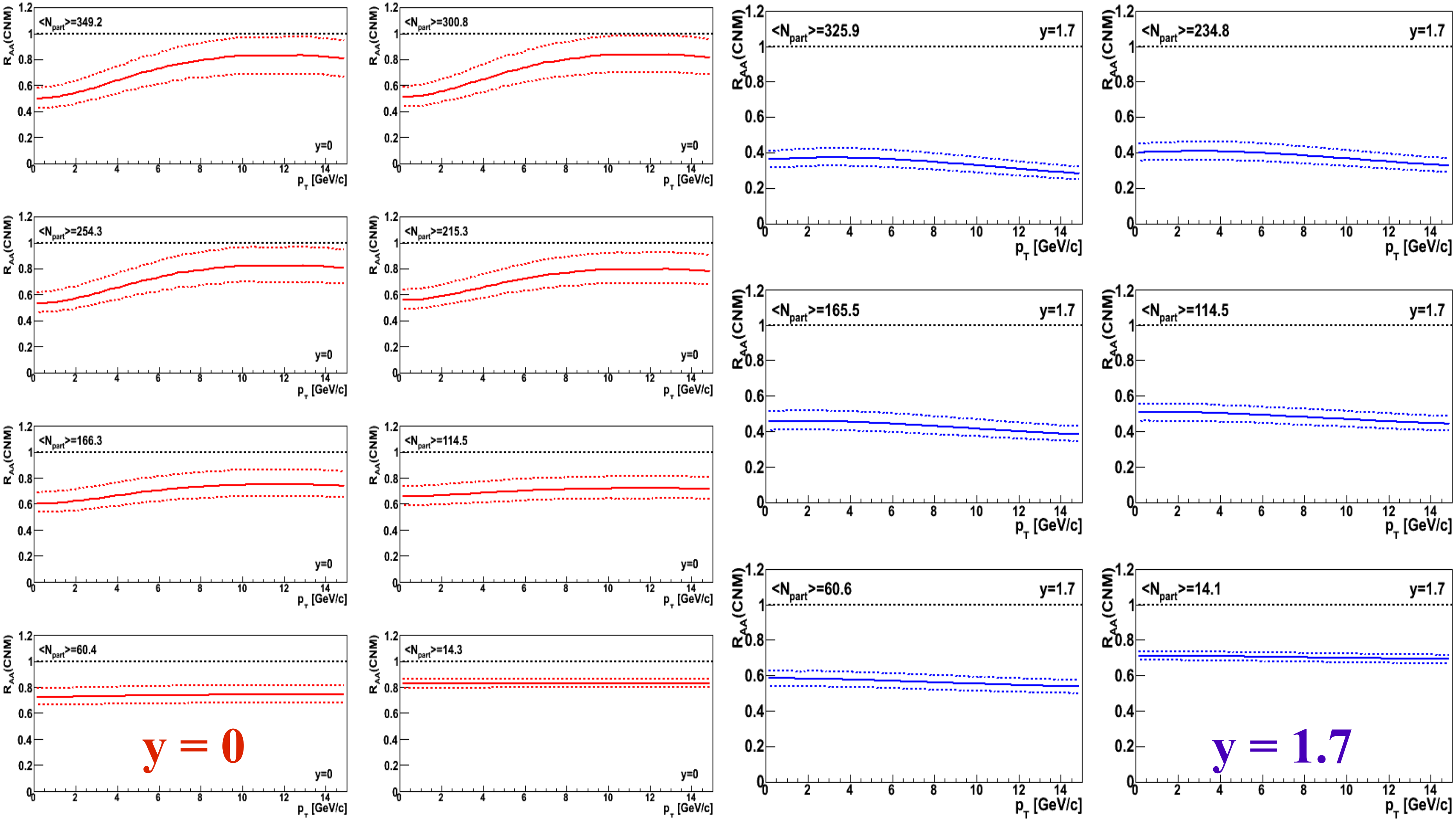
Suppression **beyond CNM** for central collisions ~ 0.5

Same suppression, within uncertainties, for both rapidities.



R_{AA}(CNM) – p_T dependence

The p_T dependence is due to shadowing alone. It will therefore be **different** at LHC, where x will be different.



Summary, conclusions

The PHENIX d+Au J/ψ data require a shadowing onset that is highly **nonlinear** with density integrated nuclear thickness.

CNM effects in d+Au have been parameterized and projected for Au+Au collisions.

CNM effects on J/ψ result in, for Au+Au:

- R_{AA} of 0.55 in central collisions at y=0
- R_{AA} of 0.40 in central collisions at y=1.7

The suppression **beyond** CNM is ~ 50% at y=0 and 1.7.

CNM effects on the **p_T dependence** of R_{AA} are very significant!

Future work

Explore effect of EPS09 **uncertainty band** on conclusions.

Shadowing is presumably similar for J/ψ, ψ' and χ_c.

Breakup due to collisions with nucleons is likely **NOT** similar.

CNM suppression of J/ψ may be disproportionately due to breakup of the (much larger radius) ψ' and χ_c mesons during the initial nuclear crossing, reducing feed down to the J/ψ.

We can investigate this by measuring R_{dAu} for the ψ'.

Backup

Centrality dependence

Top: peripheral R_{dAu}.

Middle: central R_{dAu}.

Bottom: most central R_{CP}:

$$R_{CP}(0-20) = \frac{R_{dAu}(0-20)}{R_{dAu}(60-88)}$$

Taking the ratio of R_{dAu} eliminates the p+p cross section, **and** some d+Au systematic uncertainties.

The suppression at forward y is **inconsistent** with the EPS09 plus constant $\sigma_{breakup}$ calculation.